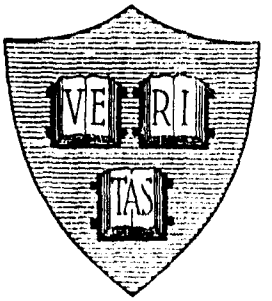
AD 408 445

(5) 234 300 63-4-2 Scale 1/1

Office of Naval Research

Contract Nonr-1866(26) NR-371-015

PULSE PROPAGATION INTO WATER



By

Hans J. Schmitt

March 18, 1963

Technical Report No. 405

Cruft Laboratory
Harvard University
Cambridge, Massachusetts

$1.60

(4) $1.60 (5) 234 300

Office of Naval Research
(13) Contract Nonr 1866(26),
(16) Proj. NR 371 015
(17) - (18) NRL (19) 16 (21) pp. A

Technical Report

on

(6) PULSE PROPAGATION INTO WATER, (7) - (8) NA

(10) by

Hans J. Schmitt

(11) March 18, 1963, (12) 16p. (13) NA

The research reported in this document was made possible through support extended Cruft Laboratory, Harvard University, jointly by the Navy Department (Office of Naval Research), the Signal Corps of the U. S. Army, and the U. S. Air Force, under ONR Contract Nonr 1866(26). Major parts of the research were also supported by the Sandia Corporation, Albuquerque, New Mexico. Reproduction in whole or in part is permitted for any purpose of the United States Government.

(14) ~~Technical Report No.~~ 405

(15)

Cruft Laboratory
Harvard University
Cambridge, Massachusetts

Requests for additional copies by Agencies of the Department of Defense, their contractors, and other Government agencies should be directed to the:

ARMED SERVICES TECHNICAL INFORMATION AGENCY
ARLINGTON HALL STATION
ARLINGTON 12, VIRGINIA

Department of Defense contractors must be established for ASTIA services, or have their "need-to-know" certified by the cognizant military agency of their project or contract.

All other persons and organizations should apply to the:

U. S. DEPARTMENT OF COMMERCE
OFFICE OF TECHNICAL SERVICES
WASHINGTON 25, D. C.

TR405 PULSE PROPAGATION INTO WATER

by

Hans J. Schmitt

Division of Engineering and Applied Physics

Harvard University, Cambridge, Massachusetts

ABSTRACT

The transmission of short unidirectional plane-wave pulses into water and solutions of sodium chloride has been investigated experimentally. The time sequence of the transient response for incident pulses with a duration of several nanoseconds is observed at various depths in the electrolyte. The dispersion of the pulse is mainly due to the ionic conductance of the solution. For very rapid polarizing forces the relaxation associated with the hindered rotation of the water molecules also contributes to the dispersion. Unlike the exponential attenuation of sinusoidal signals in conducting media, for short pulses the maximum response ultimately follows an inverse cube law with increasing depth. The experimental results are compared to the calculated transient response obtained from an approximate theory. The agreement is excellent.

INTRODUCTION

The peculiar dispersion of transient electromagnetic signals in conducting media has been discussed theoretically in several recent papers. Richards [1] analyzes the radiation of short unidirectional pulses by electric and magnetic dipoles immersed in a conducting medium. The asymptotic behavior of the transient response at great distances from the source excited by a Dirac impulse shows a smooth but relatively fast rise followed by a slow drop in the signal level. The maximum of the response proceeds at a slow speed. The speed, moreover, decreases with distance and, coincidentally, is equal to the sound velocity at a distance of about 1 km . The amplitude of the maximum response decreases in a manner inversely proportional to the cube of the distance, while the entire pulse is progressively smoothed out in time resulting from the increase in relative importance of lower frequency components at larger distances. This asymptotic behavior has been directly derived by Zisk [2] using a saddlepoint integration in the transfer integral. Anderson and Moore [3] have investigated the energy frequency spectrum of electromagnetic pulses in a conducting medium.

For communication purposes, for example through sea water, pulse excitation does not appear advantageous, since for any appreciable distance, i.e., more than 1 m , the energy contained in the higher frequency components of the pulse is essentially dissipated. Also the

long-time spread in the response at greater distances prevents rapid modulation of the pulse sequence in amplitude or pulse position. Pulse dispersion in conducting media is also important in the study of shielding effectiveness for transient electromagnetic signals. Harrison [4] investigated the pulse transmission through metallic plates and shielding enclosures using a high-speed computer.

The radiation of pulses, for example under water, is difficult to investigate experimentally since any physical antenna in itself represents a dispersive system [5], [6], which has to be taken into account for a comparison with theoretically determined responses. A simpler situation which can be directly subjected to experimental comparison is the transmission of normally incident plane unidirectional pulses into a conducting medium. The analogy between TEM-mode propagation and transmission-line propagation allows the observation of the transient response inside a coaxial line, as indeed the original analytical solution of the propagation of transients in lossy media has been specifically concerned with dispersion in transmission lines [7], [8].

It is the aim of this investigation to give a comparison of experimental observations and analytical results for the dispersion of short pulses propagating through an air-liquid interface to various depths in water or aqueous electrolytic solutions of different conductivity. In particular, the transition from a relatively well-preserved pulse shape at a small

depth in the conducting solution to the ultimate asymptotic form for large depths is investigated. In aqueous solutions a loss mechanism and an associated dispersion arise due to the hindered rotation of the water molecules in addition to the ionic conductivity. Although the relaxation time, $\tau_R \sim 0.94\ 10^{-11}$ sec [9] is extremely short compared to the rise time of the duration of the pulse actually used, the absorption is shown experimentally in the smoothing out of the initial discontinuity of the precursor signal. For solutions with negligible conductivity an approximate analysis indicates how, in principle, the relaxation time can be measured directly by observation of the transient response.

EXPERIMENTAL PROCEDURE

For the detailed observation of pulse dispersion over relatively small distances repetitive pulses with durations of 20 nsec and 60 nsec and a rise time of approximately 0.25 nsec supplied by a mercury switch pulse generator have been used. The pulses are led through a 20 dB matched attenuator and a 3' section of 50 ohm cable (RG8U) to the test line. The test line consists of an air-filled stainless steel coaxial line with matched characteristic resistance of 50 ohms and a length of 1 meter. Mounted in a vertical position it is partially or fully filled with the electrolytic solution through a small inlet near the bottom. The liquid is contained by a thin Teflon membrane with lateral support sleeves, Fig. 1. With a thickness of the membrane of 0.025" no degrading of the pulse shape in the empty line could be observed.

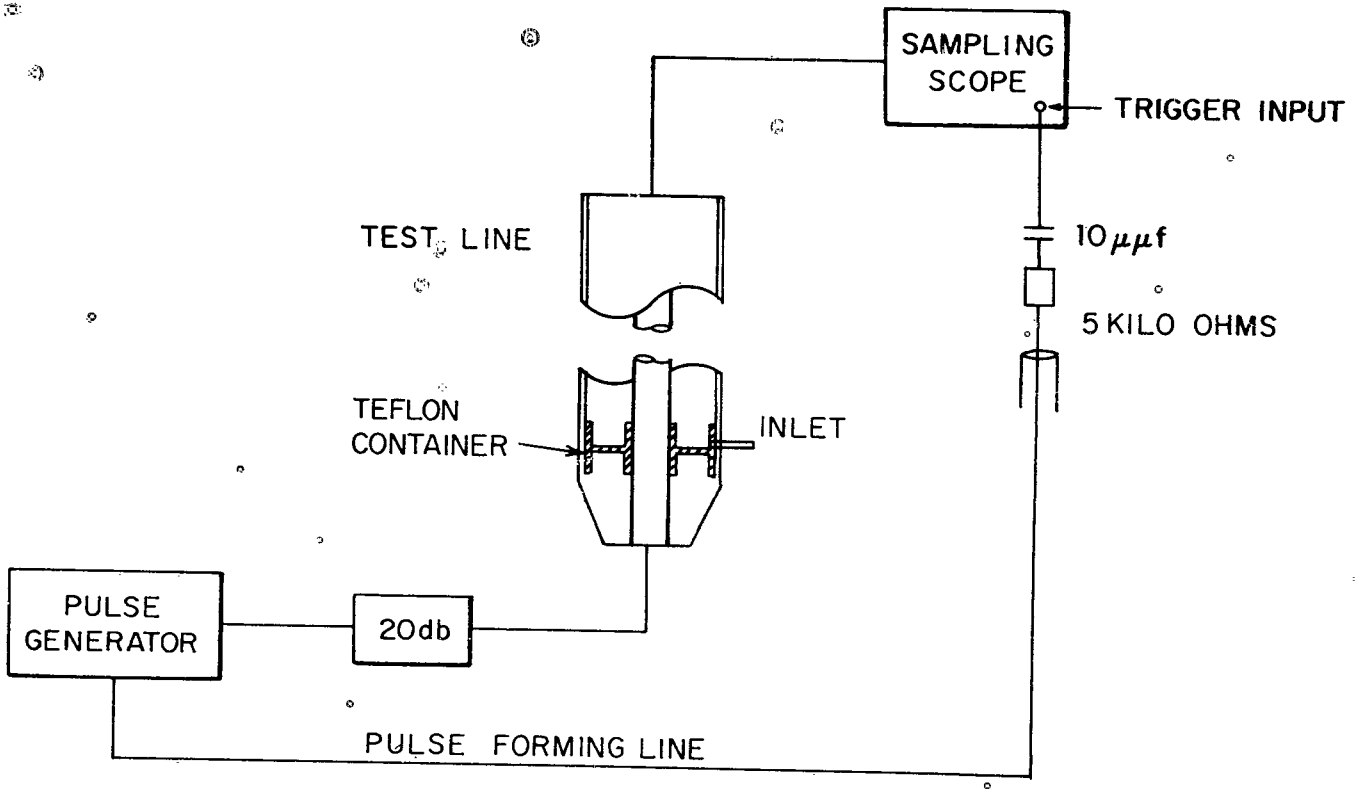


FIG. 1 EXPERIMENTAL SETUP

The test line is terminated in a reflection-free transition to a 3' section of RG 8U cable leading directly to the input of a Tektronix 611 sampling scope. The time base of the scope is triggered from the end of the pulse-forming section of coaxial line by connecting the inner conductor through a resistor of 5 kiloohms in series with a capacitor of 10 $\mu\mu$F to the trigger input. The advantage of this triggering procedure is that the initial rise of the pulse is preserved and no unnecessary degrading junctions are introduced into the transmission path of the signal. Reflections from the air-water interface are absorbed without reflection in the 20 dB attenuator.

In this scheme the transmission through a slab of liquid is measured. If the observation is restricted to the first transmitted pulse only, the signal observed on the oscilloscope is proportional to

$$V \triangleq T\,V(t, z) \tag{1}$$

where $V(t, z)$ represents the voltage at the depth z in a semi-infinite medium and T the transmission coefficient of the interface between the liquid and air. For a liquid of complex relative dielectric constant $\epsilon_r = \epsilon_r' + j\epsilon_r''$ and a conductivity σ the plane wave transmission coefficient is

$$T = \frac{2}{1 + \dfrac{1}{\sqrt{\epsilon_r' - j\left(\epsilon_r'' + \dfrac{\sigma}{\omega \epsilon_o}\right)}}} \tag{2}$$

In the frequency range relevant to the experiment, the real part of the dielectric constant of water is $\epsilon_r' = 78.2$. The loss term varies

with frequency. Hence, T lies between 1.8 and 2.0 . The additional dispersion in this transmission is negligible and for the correlation of the observed response to the results calculated for a semi-infinite liquid medium a value of 1.8 has been assumed throughout. The elimination of multiple reflections is automatically achieved for solutions with sufficiently high conductivity in view of the relatively large absorption in the conducting medium. For extremely low conductivity the dispersion is small enough so that for the chosen pulse length the secondary reflections are separated in time.

Electrolytic solutions were prepared by dissolving sodium chloride in distilled water. All measurements were taken at room temperature (25° C). The conductivity values, σ , are calculated from tabulated values of loss tangents measured at 10^5 c/sec [10] . The following values are considered

distilled water	$\sigma \sim 10^{-4}$ [mho]
0.01 molar	$\sim$ 0.1
0.03 "	.315
0.1 "	1.0
0.3 "	2.75
0.5 "	4.33

Sea water corresponds approximately to a 0.5 molar solution of sodium chloride.

EXPERIMENTAL RESULTS AND DISCUSSION

The original unidirectional pulse with a duration of 20 nsec after transmission through the empty test line is shown in Fig. 2. The rise time observed is essentially that of the oscilloscope, approximately 0.35 nsec. Negligible ringing is observed at the leading edge. It results from internal reflections in the pulse generator and coaxial junctions. The trailing edge for both the pulse shown and the longer pulse (60 nsec) reveals a small rounding-off, similar to the effect which arises if a small capacitance is connected in parallel to a transmission line. Such capacitive effects occur due to junctions of coaxial systems with different geometry and the behavior of electromagnetic fields in the junction zone [11].

(1) Relaxation Dispersion

For the test line filled with distilled water to three different levels, the transient response is shown in Fig. 3. In distilled water the absorption over distances considered here, i.e., up to about 1 meter, is negligible. The sequence of pulses arising from multiple reflections in the water slab is clearly shown in the exposure with the longer time scale. The exposures with the shorter time scale of 1 nsec per major division show the leading edge of the first pulse transmitted only. While for a non-conducting non-dispersive medium the rise time of the incident

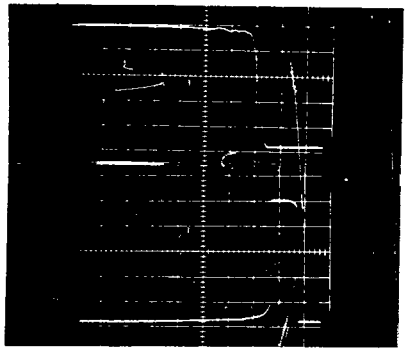
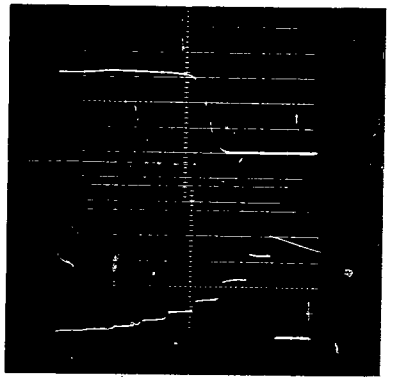
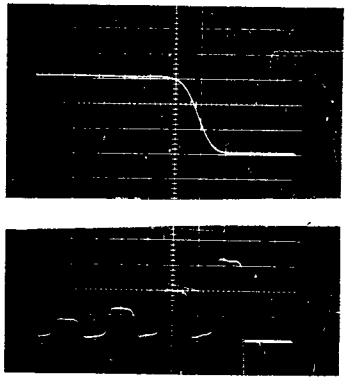
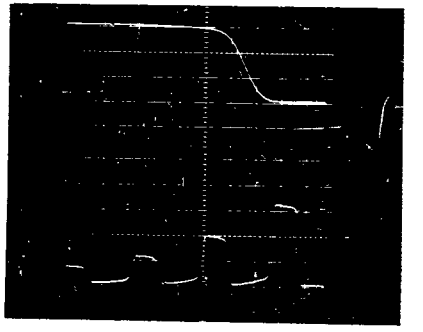


FIG. 2 TRANSMISSION OF 20 nsec PULSE THROUGH EMPTY TEST LINE.
1 $^{nsec}/_{div}$ AND 20 $^{nsec}/_{div}$







(a) (b) (c)

FIG. 3 TRANSMISSION OF 20 nsec PULSE INTO DISTILLED WATER. INPUT VOLTAGE 0.48 V, TIME SCALE 1 $^{nsec}/_{div}$ AND 20 $^{nsec}/_{div}$, SENSITIVITY 50 m $V/_{div}$
(a) z = 0.35 m , (b) z = 0.7 m, (c) z = 0.918 m

pulse should be preserved, it is seen that the leading edge is smoothed out progressively with increasing distance. This effect arises from the relaxation dispersion associated with the hindered rotation of the water molecules. For a simple relaxation effect, the complex dielectric constant of a non-conducting medium is represented by [12]

$$\epsilon_r = \epsilon_\infty' + \frac{S}{1 - j\omega\tau_R} \tag{3}$$

where $S = \epsilon_S' - \epsilon_\infty'$ defines the total decrease in the dielectric constant from ϵ_S' measured statically and ϵ_∞' measured far beyond the relaxation frequency. The response observed at some depth z below the surface at $z = 0$ to a Dirac pulse incident from air, (velocity of light c) is

$$V(t,z) = \frac{1}{\pi} \int_{-\infty}^{+\infty} \frac{e^{-j\omega t + j\frac{\omega}{c} z \sqrt{\epsilon_\infty' + S/(1-j\omega\tau_R)}}}{1 + \sqrt{\epsilon_\infty' + S/(1 - j\omega\tau_R)}} d\omega \tag{4}$$

Since the actual pulse has a finite rise time, the integration should be extended only up to frequencies of approximately 1000 Mc/sec, the limit of the oscilloscope. Hence, $\omega\tau_R << 1$ and the integral may be simplified by neglecting the dispersive term in the denominator, while retaining it in first order in the exponent,

$$V(t, z) = \frac{1}{\pi\,[1+\sqrt{\epsilon_S'}\,]} \int_{-\infty}^{+\infty} e^{-j\omega\tau - \frac{\omega^2}{4\lambda}} d\omega = \frac{2}{1+\sqrt{\epsilon_S'}} \sqrt{\frac{\lambda}{\pi}}\, e^{-\lambda\tau^2} \tag{5}$$

where $\tau = t - \frac{z}{c}\sqrt{\epsilon_S'}$ is the delay in a non-dispersive medium, and

$$\lambda = \frac{1}{2} \frac{c\sqrt{\epsilon_S'}}{z\,\epsilon_S' \tau_R}$$

The response to a Dirac pulse is proportional to the time derivative of the response to a step function: If the incident signal is given by

$$V^i(t, 0) = \begin{cases} 0 & t < 0 \\ V_o & t > 0 \end{cases}$$

or by the leading part of a sufficiently long pulse, the response is

$$V_S(t, z) = \frac{2 V_o \sqrt{\frac{\lambda}{\pi}}}{1 + \sqrt{\epsilon_S'}} \int_{f(\lambda)}^{\tau} e^{-\lambda \tau'^2} \, d\tau' \qquad (6)$$

The lower limit can be determined by inspection of the behavior at large times. The integration results in an error function

$$V_S(t, z) = \frac{1}{1 + \sqrt{\epsilon_S'}} \left(\phi(\sqrt{\lambda}\,\tau) + 1 \right) \qquad (7)$$

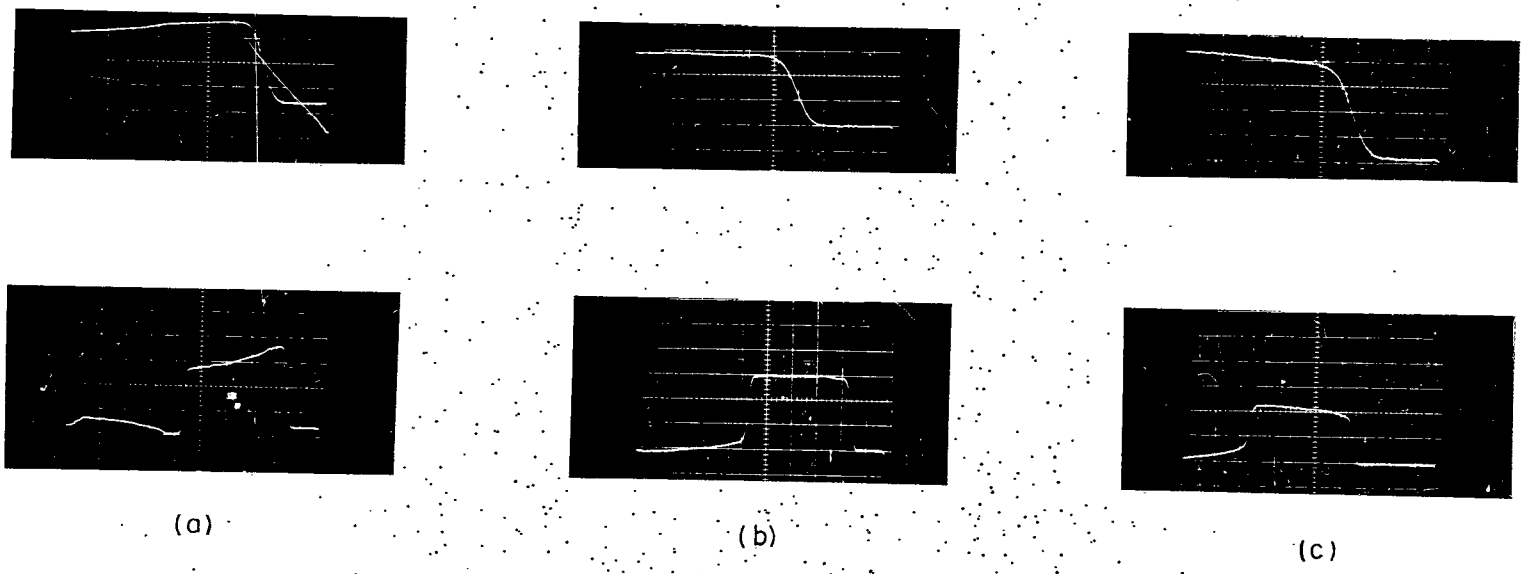
It is seen in Fig. 3 that the response to a step indeed resembles the behavior as given by Eq. 7. The steepest rise for step excitation occurs in this approximation at $\tau = 0$ and is numerically given by Eq. 5 after multiplication with the amplitude factor V_o. The gradient at $\tau = 0$ decreases in a manner proportional to the square root of the depth

of observation. The evaluation of the rise times observed experimentally gives an average value of the relaxation time $\tau_R \sim 1.24\ 10^{-11}$ sec, about 30 % larger than the published value. For an accurate determination, the integral 4 has to be solved. Although interesting for a discussion of transient propagation in media showing relaxation dispersion, it is not attempted here.

It should be noted that in all later results on the transient response in conducting liquids, the initial precursor is not a discontinuous step but shows, in principle, a smooth transition similar to that found for distilled water.

(2) Conductivity Dispersion

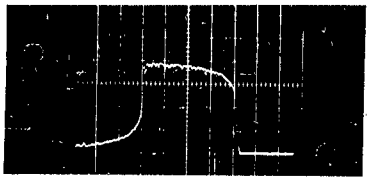
The experimental results for pulse dispersion in salt water are reproduced in Figs. 4-8. For the lowest concentration, a 0.01 molar solution of NaCl with $\sigma \sim 0.1$ mho, Fig. 4, only the response to a 20 nsec pulse is shown, since the response to a longer pulse would be perturbed due to insufficient attentuation between multiple reflections over shorter distances. Indeed, the effect of first multiply-reflected pulse is still slightly visible in the observation of the 60 nsec pulse for the next higher concentration ($\sigma = 0.315$) over the smallest depth measured, Fig. 6a. All other responses represent essentially the directly transmitted pulse only.



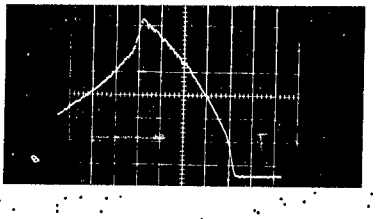
(a) (b) (c)

FIG. 4 TRANSMISSION OF 20 nsec PULSE INTO 0.01 MOLAR NaCℓ SOLUTION. INPUT VOLTAGE 0.48 V, TIME SCALE 1 $^{nsec}/_{div}$ AND 5 $^{nsec}/_{div}$

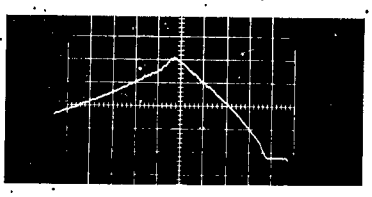
(a) z = 0.35 m SENSITIVITY 20 m $^{V}/_{div}$ (b) z = 0.7 m SENSITIVITY 10 m $^{V}/_{div}$ (c) z = 0.918 m SENSITIVITY 5 m $^{V}/_{div}$ AND 10 m $^{V}/_{div}$



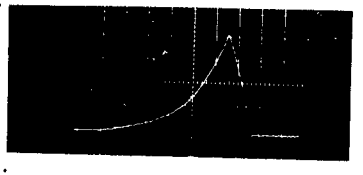
(a)



(b)



(c)



(d)

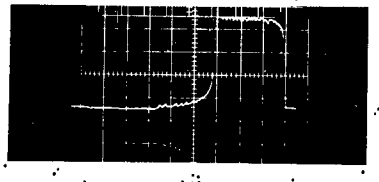
FIG. 5 TRANSMISSION OF 20 nsec PULSE INTO 0.03 MOLAR NaCl SOLUTION. INPUT VOLTAGE 4.8 V

(a) z = 0.35m, 5 nsec/div 50 mV/div

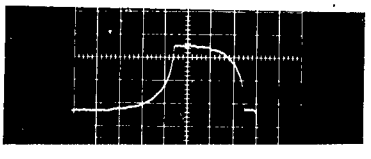
(b) z = 0.7m , " , 10 mV/div

(c) z = 0.918m , " , "

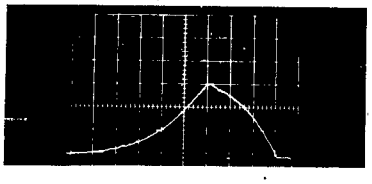
(d) z = " , 20 nsec/div , "



(a)



(b)



(c)

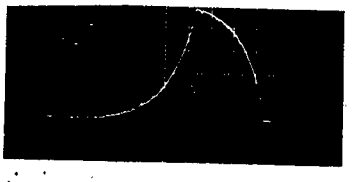
FIG. 6 SAME AS FIG. 5, PULSE DURATION 60 nsec

(a) z = 0.35m, 20 nsec/div, 50 mV/div

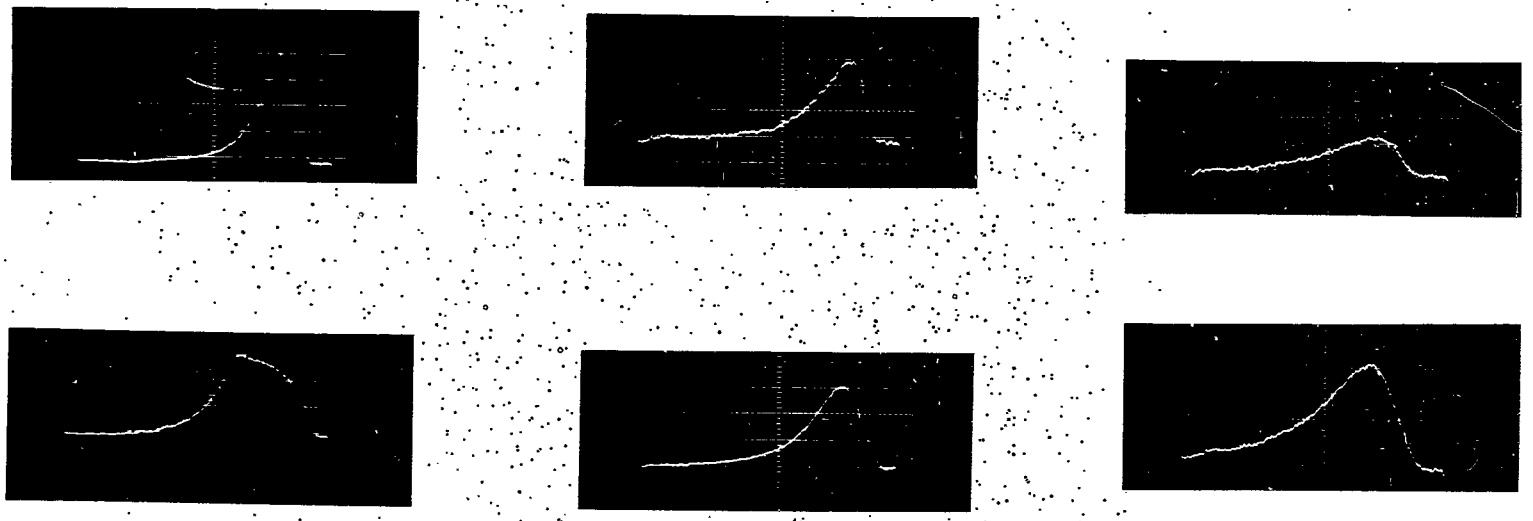
(b) z = 0.525m, " , "

(c) z = 0.7m , " , 20 mV/div

(d) z = 0.918 m, " , "



(d)



(a) (b) (c)

FIG. 7 TRANSMISSION OF PULSES INTO 0.1 MOLAR NaCl SOLUTION. INPUT VOLTAGE 4.8 V

	z	TIME SCALE	SENSITIVITY 20 nsec PULSE, (UPPER)	60 nsec PULSE (LOWER)
(a)	0.35m	20 nsec/div.	10 mV/div	20 mV/div
(b)	0.70m	50 nsec/div	2 mV/div	5 mV/div
(c)	0.918m	50 nsec/div	2 mV/div	2 mV/div

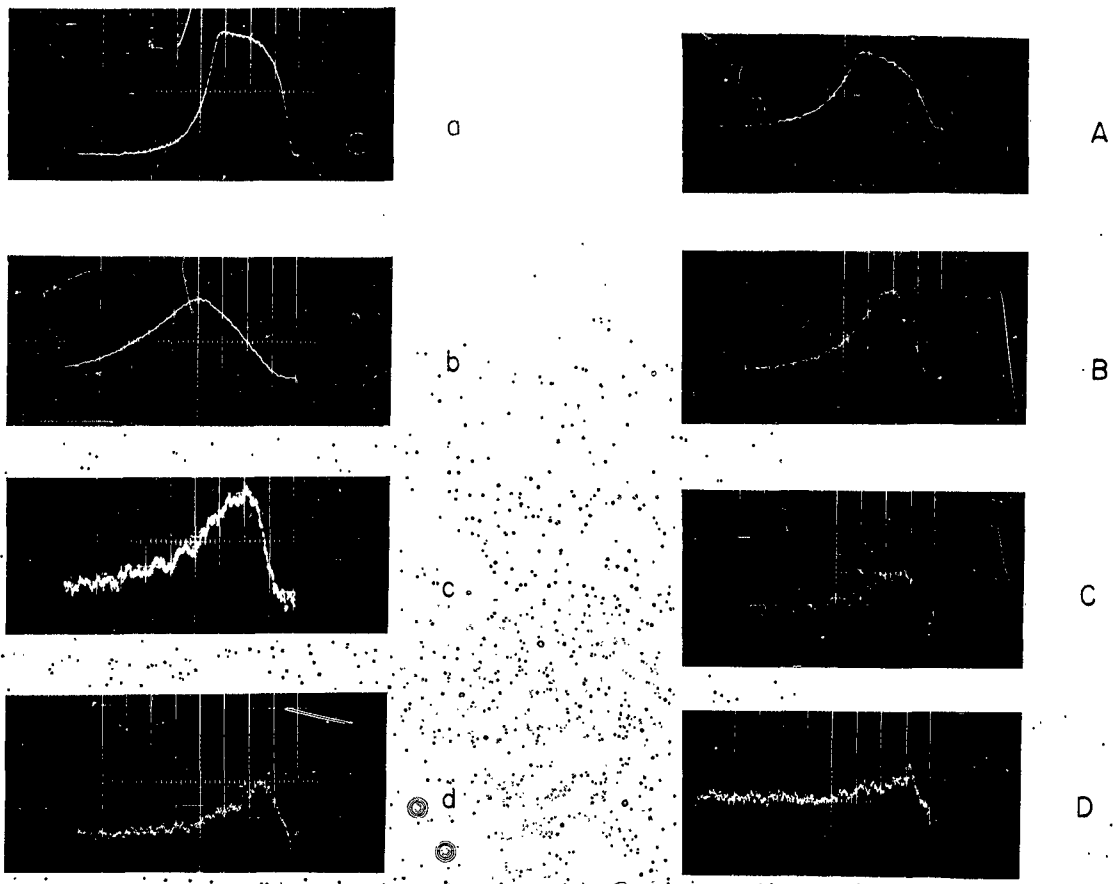


FIG. 8 TRANSMISSION OF 60 nsec PULSES INTO ELECTROLYTES. INPUT VOLTAGE 4.8 V.

KEY a – d, 0.3 MOLAR NaCl SOLUTION
A – D, 0.5 MOLAR NaCl SOLUTION

	z [m]	TIME SCALE $\left[\frac{\text{nsec}}{\text{div}}\right]$	SENSITIVITY $\left[\frac{\text{mV}}{\text{div}}\right]$
a	0.175	20	10
A	0.175	20	10
b	0.35	20	5
B	0.35	50	2
c	0.7	100	0.6
C	0.7	200	0.6
d	0.918	200	0.6
D	0.918	500	0.6

A qualitative appraisal of the different pulse responses observed shows that for low conductivity and a small depth of observation the initial response is a rapid rise and thereafter a slow decrease until the pulse ends, Fig. 4a. (Time increases to the left in the figures). As the depth of observation is increased, the top of the pulse flattens, Fig. 4b , and with further increases in depth ultimately starts rising as in Fig. 4c. For a larger conductivity, Fig. 5, $\sigma = 0.315$, the same transition takes place at a much reduced depth of observation. For the same depth as in Fig. 4a, it is seen in Fig. 5a, that the pulse top already starts rising. If, for the higher conductivity, the point of observation is moved deeper into the electrolyte the initial sharp step decreases in amplitude, Fig. 5b and 5c , and also Fig. 6a-d for the longer test pulse. After the termination of the pulse a slow drop in voltage is observed.

With increasing conductivity, Fig. 7 and Fig. 8 , this initial transition occurs at even shorter distances, in a depth of a few centimeters. In the range of depth considered in the experiment, the transient response no longer resembles the original pulse. With increasing distance, e.g. for a depth of more than 50 cm in sea water, an asymptotic pulse shape is observed which shows an initial smooth rise and a slightly slower decay of the signal level in time. With increasing distance and increasing conductivity the entire pulse is progressively spread out in time. In sea water, for example, a 60 nsec pulse is spread to about 1.5 μ sec in a distance of roughly 1 meter.

A point of recent discussion Eqs. 1 - 3 has been the fact that the maximum amplitude of the transient response to short unidirectional pulses decreases only as $1/z^3$ as compared to the much more rapid exponential attenuation of continuous wave signals. While, of course, each Fourier component of the original pulse spectrum is exponentially attenuated, the slower damping of the transient response is a result of dispersion and the increasing importance of lower frequency components at large distances.

In the case of a plane-wave transition into the liquid, the transient response at z for an incident step function signal of amplitude V_o is

$$V_S(z,t) = \frac{2j\,V_o}{2\pi} \int_{-j\infty}^{+j\infty} \frac{e^{pt - p\frac{z}{c}\sqrt{\epsilon_r' + \frac{\sigma}{p\epsilon_o}}}}{p\left[1 + \sqrt{\epsilon_r' + \frac{\sigma}{p\epsilon_o}}\right]}\,dp \quad . \tag{8}$$

Relaxation losses have been neglected in Eq. 8. In view of the large value of $\epsilon_r' = 78.2$ the first term in the bracket in the denominator may be neglected too. With the substitution of $p = x - \frac{\sigma}{2\epsilon_o\epsilon_r'}$ it follows from Eq. 8 that

$$V_S(z,t) = \frac{-2j\,V_o}{2\pi\sqrt{\epsilon_r'}}\, e^{-\frac{\sigma}{2\epsilon_o\epsilon_r'}t} \int_{\frac{\sigma}{2\epsilon_o\epsilon_r'}-j\infty}^{\frac{\sigma}{2\epsilon_o\epsilon_r'}+j\infty} \frac{e^{xt - \frac{z}{c}\sqrt{\epsilon_r'}\sqrt{x^2 - \left(\frac{\sigma}{2\epsilon_o\epsilon_r'}\right)^2}}}{\sqrt{x^2 - \left(\frac{\sigma}{2\epsilon_o\epsilon_r'}\right)^2}}\,dx \quad . \tag{9}$$

This integral is listed in [1.3] . The approximate transient response to an incident step function signal at a depth z is

$$V_S(z,t)\begin{cases}\dfrac{2V_o}{\sqrt{\epsilon_r'}}\, e^{-\frac{\sigma}{2\epsilon_o\epsilon_r'}t}\, J_o\left(j\dfrac{\sigma}{2\epsilon_o\epsilon_r'}\sqrt{t^2-\left(\dfrac{z}{c}\sqrt{\epsilon_r'}\right)^2}\right) & t>\dfrac{z}{c}\sqrt{\epsilon_r'}\\ 0 & t<\dfrac{z}{c}\sqrt{\epsilon_r'}\end{cases} \tag{10}$$

The transient response calculated from Eq. 10 is plotted in Fig. 9 as a function of the depth of observation for the three highest conductivities used in the experiment. The transient response of a pulse of duration T_o sec, follows from Eq. 10 in view of the linearity of the system and causality.

$$\begin{aligned} V_p(z,t) &= V_S(z,t) && t<\frac{z}{c}\sqrt{\epsilon_r'}+T_p\\ &= V_S(z,t)-V_S(z,t-T) && t>\frac{z}{c}\sqrt{\epsilon_r'}+T_p \end{aligned} \tag{11}$$

The time sequence of the transient signal calculated from Eqs. 10 and 11 is plotted in Fig. 10 and 11 for $\sigma = 0.315$ mho and $\sigma = 1$ mho. It is clearly seen that the calculated response agrees precisely with the observed wave shapes. A small deviation between the slope of the pulse top for the long exciting pulse in the case of $\sigma = 0.315$ mho and $z = 0.35$ meter is explained by the fact, that here in the experimental observation, the secondary reflection arrives before the direct pulse has ended. This reflection essentially adds a small component to the later part in the direct pulse response.

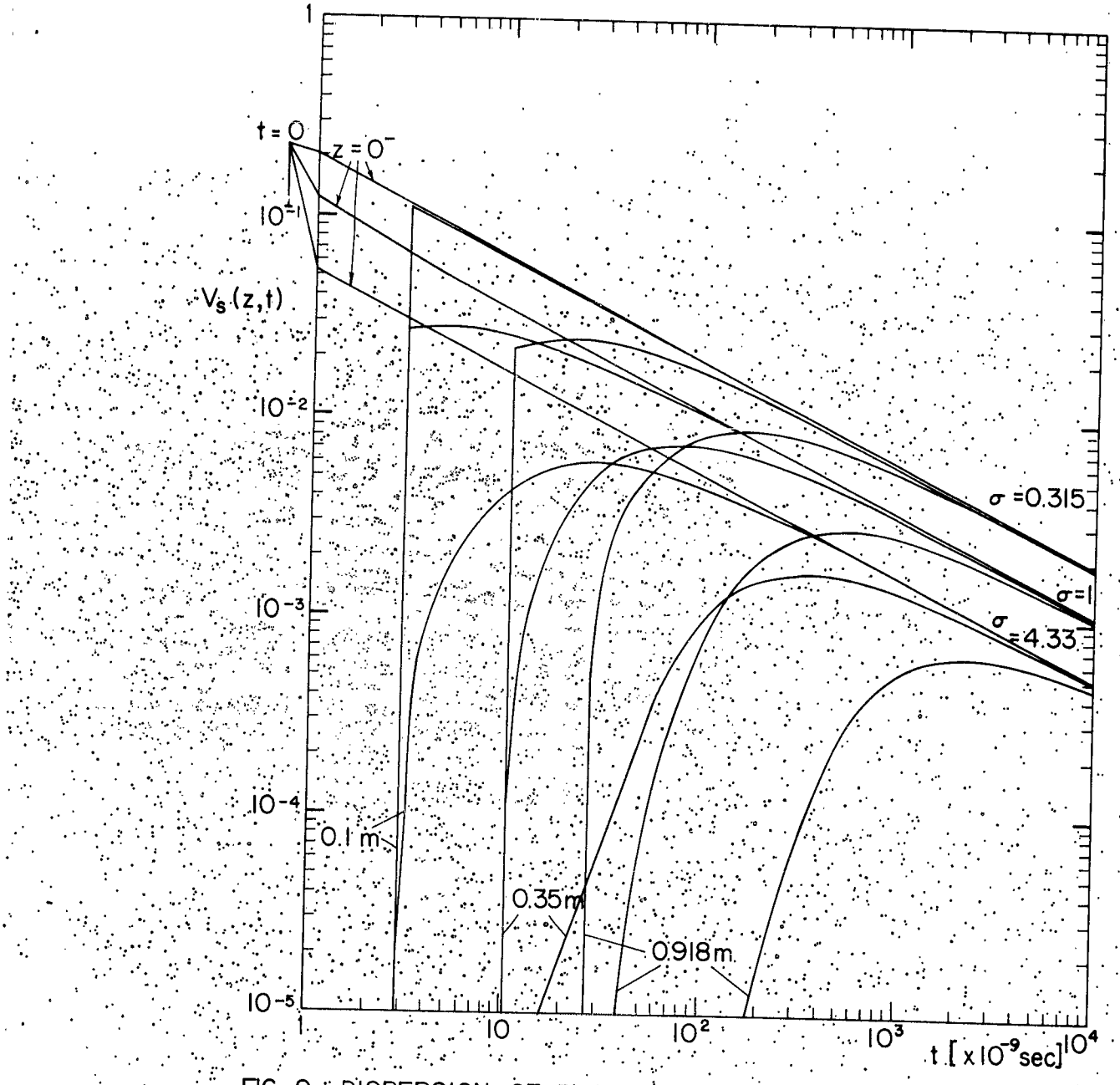


FIG. 9 DISPERSION OF PLANE ELECTROMAGNETIC WAVE WITH STEP FUNCTION TIME DEPENDENCE IN CONDUCTING MEDIA.

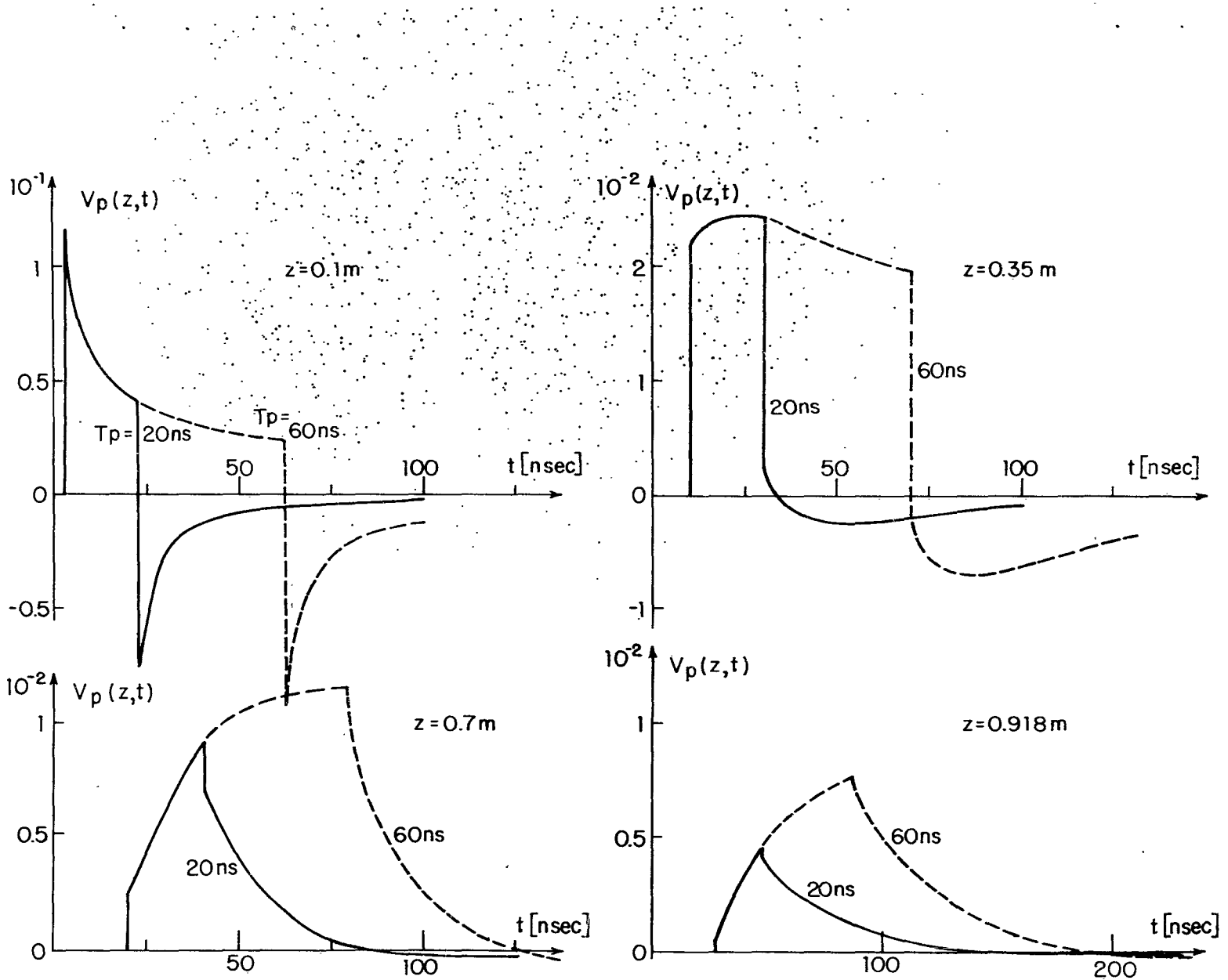


FIG. 10 DISPERSION OF PLANE UNIDIRECTIONAL PULSE IN CONDUCTING MEDIUM. CONDUCTIVITY σ = 0.315 mho (0.03 MOLAR SOLUTION NaCℓ)

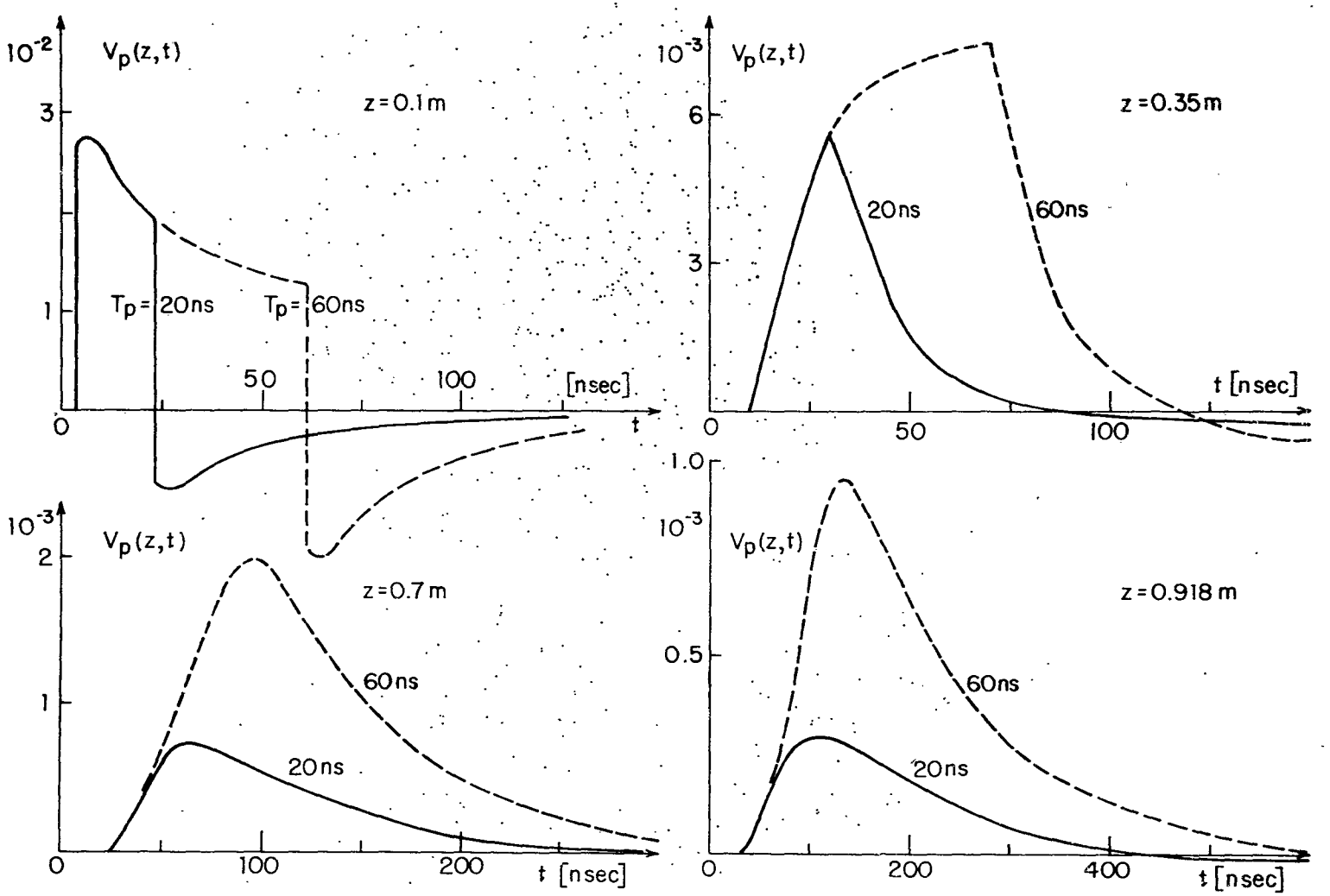


FIG. 11 DISPERSION OF PLANE UNIDIRECTIONAL PULSE IN CONDUCTING MEDIUM CONDUCTIVITY σ = 1 mho (0.1 MOLAR NaCℓ SOLUTION)

For greater depths or larger conductivities the shape of the transient response due to an incident step function signal is given by the asymptotic form of Eq. 10

$$V_S(z,t) \sim \frac{2}{z\sqrt{\frac{\pi\sigma t}{\epsilon_o z^2}}}\, e^{-\frac{\sigma}{4c^2\epsilon_o}\frac{z^2}{t}} \qquad (12)$$

The signal ultimately decreases in a manner inversely proportional to distance. For an incident pulse with a duration T_p << rise time of the step function response, the corresponding approximation is

$$V_p(z,t) \sim \frac{2T_p}{z^3\sigma^2\sqrt{\frac{\pi}{\epsilon_o}}}\, \frac{e^{-\frac{\sigma}{4c^2\epsilon_o}\frac{z^2}{t}\left(\frac{\sigma}{4c^2\epsilon_o}\frac{z^2}{t}-\frac{1}{2}\right)}}{\left(\frac{t}{\sigma z^2}\right)^{\frac{3}{2}}} \qquad (13)$$

Asymptotically, the signal decreases in a manner proportional to z^{-3}

$$z^3 V_p(z,t) \sim \frac{T}{\sigma^2} f\left(\frac{t}{\sigma z^2}\right)$$

This response is shown in Fig. 12 and is a good approximation of the experimental result for σ = 4.33 mho (~ sea water). It is noteworthy that for pulses the response changes polarity and approaches the steady state from the negative side. A comparison of calculated maxima of the transient response and measured values for both the short pulse of

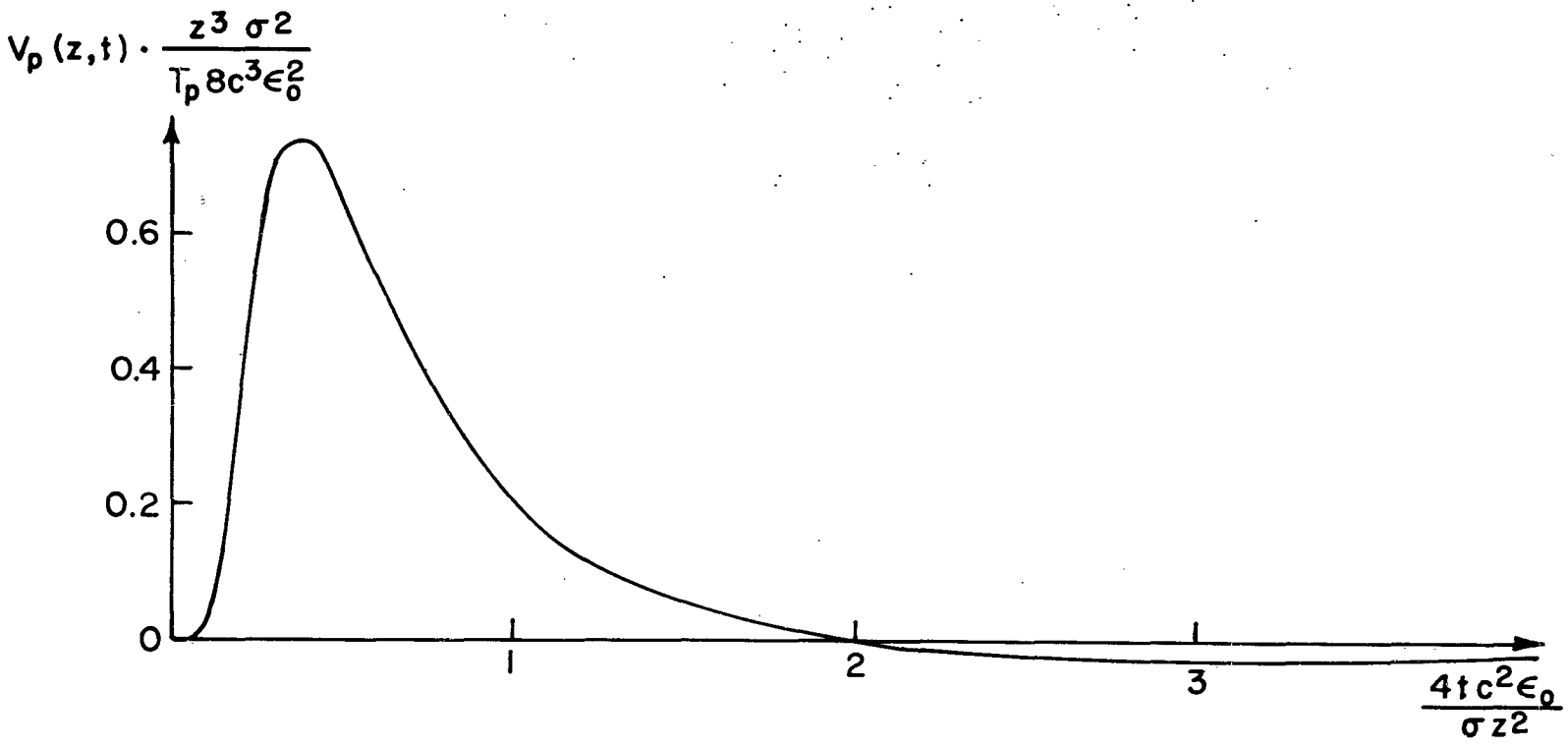


FIG. 12 DISPERSION OF PLANE UNIDIRECTIONAL PULSE IN CONDUCTING MEDIUM. ASYMPTOTIC FORM FOR HIGH CONDUCTIVITY AND LARGE DEPTH OF OBSERVATION.

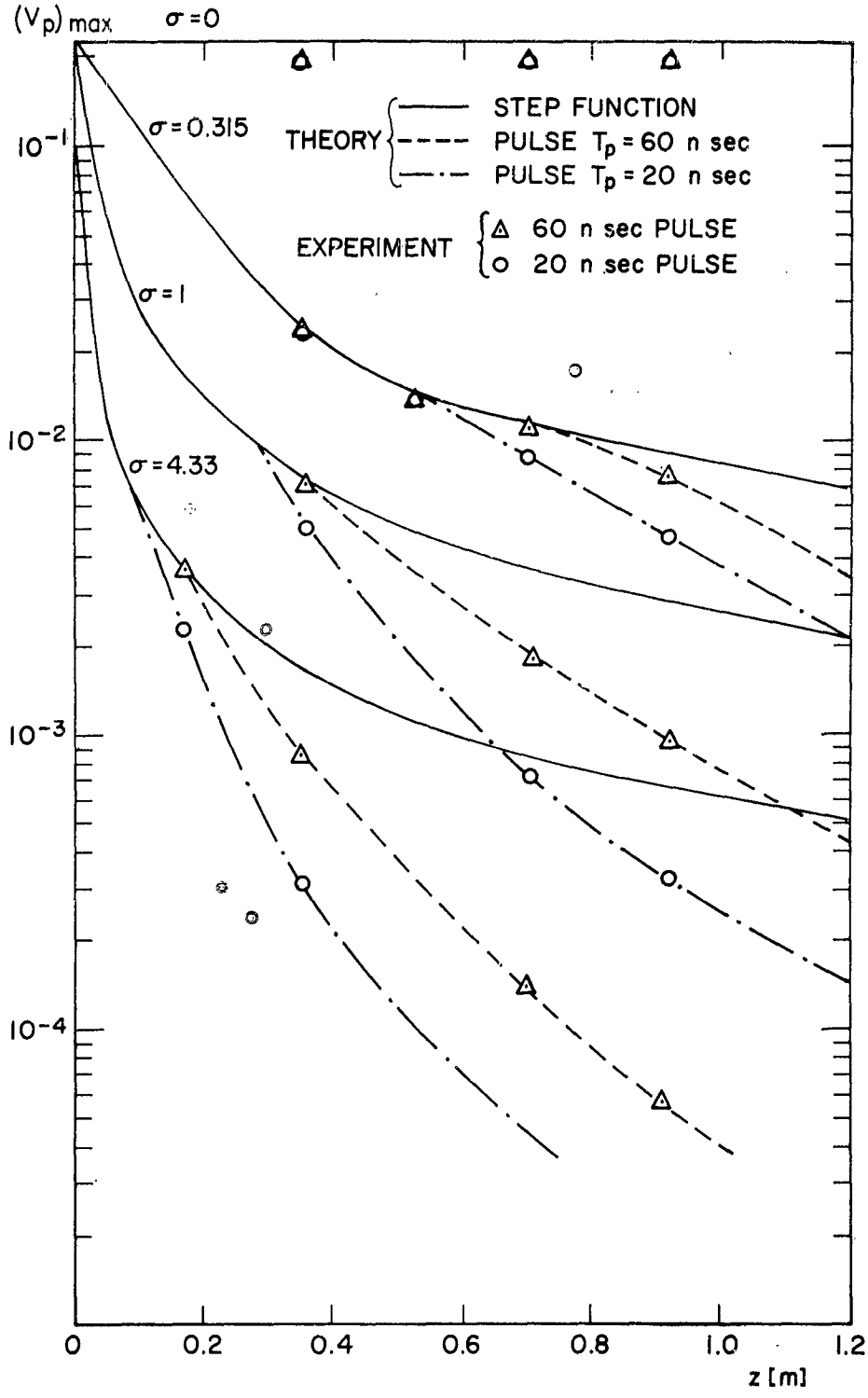


FIG. 13 MAXIMUM RESPONSE OF TRANSIENT PULSES PROPAGATING INTO CONDUCTING MEDIUM

20 nsec and the longer pulse of 60 nsec is shown in Fig. 13 . The agreement is excellent.

CONCLUSIONS

The experimental observation of pulse propagation into conducting media and the good agreement obtained with an approximate theory substantiates the arguments previously made against the feasibility of pulse communication under water. The inherent dispersion and the slow speed of propagation are disadvantages in the rapid transfer of information, and energy contained in the higher frequency components is wasted for communication over greater distances.

The results obtained are also directly applicable to problems arising in shielding against radio interferences. The expression 10 , if multiplied by a factor two, gives directly the electric field strength behind a conducting wall illuminated by a plane wave with a unidirectional step in electric field strength. The same applies to Eq. 11 for an incident pulse and the corresponding approximations 12 and 13 . The condition to be imposed is that multiple reflections should be negligible, or they may be taken into account individually and added to form the response for a finite slab.

The agreement between experimentally observed pulse dispersion due to relaxation processes with the approximate theoretical result is not entirely satisfactory. It should be possible to extend this analysis, particularly with respect to relaxation processes that have critical times comparable to the pulse duration and the pulse rise time.

ACKNOWLEDGMENTS

The author wishes to thank Professor Ronold W. P. King for support and stimulation for this investigation. Thanks are due to Mr. R. Ryquist for pointing out the inverse Laplace transform.

REFERENCES

1. P. I. Richards, "Transients in Conducting Media", IRE Trans. A.P.-6, pp. 178-182, April, 1958.

2. S. H. Zisk, "Electromagnetic Transients in Conducting Media", IRE Trans. A.P.-8, pp. 229-230, March, 1960.

3. W. L. Anderson and R. K. Moore, "Frequency Spectra of Transient Electromagnetic Pulses in a Conducting Medium", IRE Trans. A.P.-8, pp. 603-607, November, 1960.

4. C. W. Harrison, Sandia Corp. Report, to be published.

5. H. J. Schmitt, "Transients in Cylindrical Antennas", Proc. IEE, Part C, Monograph No. 377 E .

6. T. T. Wu and R. W. P. King, "Transient Response of Linear Antennas Driven from a Coaxial Line", IRE Trans. A.P.-11, pp. 17-23, January, 1963.

7. K. W. Wagner, Elektromagnetische Wellen, Birkhauser Verlag, Basel and Stuttgart, 1953.

8. R. W. P. King, Encyclopedia of Physics , Vol. XVI, Electric Fields and Waves, "Quasi-Stationary and Nonstationary Currents", p. 231, Springer-Verlag, Berlin, 1958.

9. G. B. Birks, Progress in Dielectrics , Vol. III, John Wiley Inc., New York 1961.

10. A. R. von Hippel , Dielectric Materials, John Wiley Inc., New York, 1954.

11. R. W. P. King, Transmission Line Theory, McGraw-Hill Co., New York, 1955.

12. A. R. von Hippel, Dielectrics and Waves, p. 176 , John Wiley Inc., New York 1954.

13. W. Magnus and F. Oberhettinger, "Special Functions of Mathematical Physics", Chelsea Publishing Company, New York, 1949.

Activity Supply Officer
Building 2504, Charles Wood Area
Fort Monmouth, New Jersey (50)
Attn: Director of Research

Commanding Officer
Office of Naval Research
Navy 100, Box 39 (25)
Fleet Post Office
New York, New York

Armed Services
Technical Information Agency
Arlington Hall Station (10)
Arlington 12, Virginia
Attn: TIPDR

The Director
Naval Research Laboratory
Washington 25, D. C. (6)
Attn: Technical Information Office

Commander, AF CRL
AFRD, ARDC, CRRLC
Laurence G. Hanscom Field (4)
Bedford, Massachusetts
Attn: Electronics Research Directorate

Commanding General
Air Research and Development Command
P. O. Box 1395 (3)
Baltimore 3, Maryland
Attn: RDTRRP

Chief of Naval Research
Department of the Navy (2)
Washington 25, D. C.
Attn: Dr. A. Shostak, Code 427

Chief of Naval Research
Department of the Navy (2)
Washington 25, D. C.
Attn: Code 427

Commanding Officer
Office of Naval Research
495 Summer Street (2)
Boston, Massachusetts

Chief, Bureau of Ships
Department of the Navy (2)
Washington 25, D. C.
Attn: Code 810

Director, Air University
Library (2)
Maxwell Air Force Base
Alabama

Chief of Naval Research
Department of the Navy
Washington 25, D. C.
Attn: Code 421

Commanding Officer
Office of Naval Research
495 Summer Street
Boston, Massachusetts

Commanding Officer
Office of Naval Research
John Crerar Library Building
86 East Randolph Street
Chicago 1, Illinois

Commanding Officer
Office of Naval Research
346 Broadway
New York 13, New York

Commanding Officer
Office of Naval Research
1030 East Green Street
Pasadena, California

Commanding Officer
Office of Naval Research
1000 Geary Street
San Francisco 9, California

Head, Document Section
Technical Information Division
Naval Research Laboratory
Washington 25, D. C.

Martin A. Garstens
Magnetism Branch, Code 6450
Solid State Division
Naval Research Laboratory
Washington 25, D. C.

Commanding Officer
U. S. N. Air Development Center
Johnsville, Pennsylvania
Attn: NADC Library

Commander
U. S. N. Air Development Center
Johnsville, Pennsylvania
Attn: AAEL

Chief, Bureau of Aeronautics
Department of the Navy
Washington 25, D. C.
Attn: El-1

Engineering Librarian
Convair
San Diego 12, California

Dr. John E. Pippin
Applied Physics and Ferrite Devices
Sperry Microwave Electronics Co.
P. O. Box 1828
Clearwater, Florida

Engineering Library
Sperry Microwave Electronics Co.
Clearwater, Florida

Dr. Lajos Rintal
Research Division
Raytheon Company
Waltham 54, Massachusetts

Elizabeth Weeks, Librarian
Raytheon Company
28 Seyon Street
Waltham 54, Massachusetts

Report Librarian
Sylvania Electric Products Inc.
Electronic Systems Division
100 First Avenue
Waltham, Massachusetts

Document Control Center
Wayland Library
Raytheon Manufacturing Co.
Wayland, Massachusetts

J. E. Goldman
Scientific Laboratory
Ford Motor Company
Engineering Staff
P. O. Box 2053
Dearborn, Michigan

Charles C. H. Tang
Bell Telephone Labs.
Murray Hill, New Jersey

Librarian
RCA Laboratories
Princeton, New Jersey

Dr. A. Amith
RCA
Princeton, New Jersey

Commander (2)
U. S. Naval Electronics Lab.
San Diego, California

Commanding General, RCAW
Rome Air Development Center
Griffiss Air Force Base (2)
Rome, New York

Commanding General
Air Research and Development Command
P. O. Box 1395 (2)
Baltimore, Maryland
Attn: RDDDE

Commander
Air Force Cambridge Research Labs.
Laurence G. Hanscom Field (2)
Bedford, Massachusetts
Attn: CROTLS

Commander
Wright Air Development Center
Wright Patterson Air Force Base
Ohio (2)
Attn: WCLRA Library

National Security Agency
Physical Sciences Division (2)
Fort George Meade, Maryland
Attn: Dr. Alvin Mackler

Associate Prof. A. Kapriellan
Department of Electrical Engineering
University of Southern California
University Park
Los Angeles 7, California

Assistant Secretary of Defense
(Research and Development)
Research and Development Board
Department of Defense
Washington 25, D. C.

Chief of Naval Operations
Department of the Navy
Washington 25, D. C.
Attn: Op-20

Chief of Naval Operations
Department of the Navy
Washington 25, D. C.
Attn: Op-32

Chief of Naval Operations
Department of the Navy
Washington 25, D. C.
Attn: Op-413

Chief, Bureau of Aeronautics
Department of the Navy
Washington 25, D. C.
Attn: El-4

Technical Library
U. S. Naval Proving Ground
Dahlgren, Virginia

Director
Naval Ordnance Laboratory
White Oak, Maryland

Librarian
U. S. Naval Post Graduate School
Monterey, California

Air Force Office of Scientific Research
Air Research and Development Command
Washington 25, D. C.
Attn: SRY, Physics Division

Commanding General
Rome Air Development Center
Griffiss Air Force Base
Rome, New York
Attn: RCREC-4C

Commanding General
Rome Air Development Center
Griffiss Air Force Base
Rome, New York
Attn: RCR

Commander
Air Force Cambridge Research Center
230 Albany Street
Cambridge 39, Massachusetts
Attn: CRZI

Commander
Air Force Cambridge Research Center
230 Albany Street
Cambridge 39, Massachusetts
Attn: CRZM

Commander
AF Cambridge Research Laboratories
Laurence G. Hanscom Field
Bedford, Massachusetts
Attn: Dr. Hollingsworth

Commander
Wright Air Development Center
Wright Patterson Air Force Base
Ohio Attn: WCRR

Sandia Corporation
Org. 1424, Sandia Base
Albuquerque, New Mexico
Attn: Dr. C. W. Harrison, Jr

Sandia Corporation
Sandia Base
Albuquerque, New Mexico
Attn: Library Division 1922-1

Mr. Robert Turner
General Electric Company
Advanced Electronics Center
Cornell University
Ithaca, New York

Library
Airborne Instruments Lab.
Walt Whitman Road
Melville, Long Island, New York

Secretary, Working Group
Semiconductor Devices
315 Broadway, 4th Floor
New York 13, New York
Attn: AGET

Metals Research Laboratories
Electro Metallurgical Company
Box 580, Niagra Falls, New York
Attn: Mr. R. J. Gladieux

Librarian
General Electric Research Lab.
P. O. Box 1088
Schenectady, New York

Westinghouse Electric Corp.
Research Laboratories
Beulah Road, Churchill Boro.
Pittsburgh 35, Pennsylvania

Prof. O. E. H. Rydbeck
P. O. Box 266
Delmar, New Jersey

Dr. Melvin W. Aarons
611 East Genesseo Street
Fayetteville, New York

Laboratory
Airborne Instruments
Mineola, New York

Commander
Wright Air Development Center
Wright Patterson Air Force Base
Ohio
Attn: WCRRH

Commandant
Air Force Institute of Technology
Wright Patterson Air Force Base
Ohio
Attn: MCLI Library

AF Special Weapons Center
Kirtland Air Force Base
Albuquerque, New Mexico
Attn: SWOI

Headquarters
AF Missile Test Center
MU-135, ARDC
Patrick Air Force Base
Florida

U. S. Coast Guard
1300 E Street, N. W.
Washington 25, D. C.
Attn: EEE

M. A. Krivanich, Chief
System Component Branch
Electronic Warfare Division
Signal Corps Agency
White Wands Proving Ground
New Mexico

Mr. A. D. Bedrosian
Signal Corps Liaison Office
Mass. Institute of Technology
Building 26, Room 131
Cambridge 39, Massachusetts

Chief, European Office
ARDC Command
Shell Building
60 Rue Ravenstein
Brussels, Belgium

Dr. J. Anton Hofman
Ordnance Materials Res. Office
Watertown Arsenal
Watertown, Massachusetts

Acquisitions Officer
ASTIA Reference Center
Arlington Hall Station
Arlington 12, Virginia

Stanford Research Institute
Documents Center
Menlo Park, California
Attn: Mary Lee Fields

Dr. C. H. Papas
Dept. of Electrical Engineering
California Institute of Technology
Pasadena, California

Stanford Electronics Lab.
Stanford University
Stanford, California
Attn: Document Library
Applied Electronics Lab.

Department of Electrical Engineering
Yale University
New Haven, Connecticut

Librarian
Johns Hopkins University
1315 St. Paul Street
Baltimore 2, Maryland

Radiation Laboratory
Johns Hopkins University
1315 St. Paul Street
Baltimore 2, Maryland

Director, Lincoln Laboratory
Mass. Institute of Technology
Bedford, Massachusetts

Mr. John Hewitt
Document Room
Research Lab. of Electronics
Mass. Institute of Technology
Cambridge 39, Massachusetts

Professor A. Von Hippel
Mass. Institute of Technology
Lab for Insulation Research
Cambridge 39, Massachusetts

Library, Room A 229
Lincoln Laboratory
P. O. Box 73
Lexington 73, Massachusetts

K. M. Siegel, Head
Theory and Analysis Department
Willow Run Laboratories
University of Michigan
Willow Run Airport
Ypsilanti, Michigan

Librarian
National Bureau of Standards Library
Room 301, Northwest Building
Washington 25, D. C.

Librarian
U. S. Department of Commerce
National Bureau of Standards
Boulder, Colorado

Dr. Earl Callen
National Security Agency
Physical Sciences Division
Fort George Meade, Maryland

Dr. H. Campaigne
National Security Agency
Physical Sciences Division
Fort George Meade, Maryland

Chung Kung University
Electrical Engineering Department
Taipan, Taiwan
Republic of China
Attn: Professor Chao-Hsi Chou
Head, Eng. Department

Mr. D. S. Jones
Department of Mathematics
Univ. College of No. Staffordshire
Keele, Staffordshire, England

Professor Paul Sanai Mito
Osaka City University
Dept. of Engineering Sciences
12 Nishi Ogimachi Kitaku
Osaka, Japan

Donald G. Stinson
Dept. of Electrical Engr.
University of Arizona
Tucson 25, Arizona

Professor Jerome R. Singer
Div. of Electrical Engineering
University of California
Berkeley 4, California

Professor Charles Kittel
Department of Physics
University of California
Berkeley 4, California

Serials Library
Brandeis University
Waltham, Massachusetts

Professor H. G. Booker
School of Electrical Engineering
Cornell University
Ithaca, New York

Library, College of Engineering
University Heights Library
University Heights
New York University
New York 53, New York

E. A. Chapman, Librarian
Rensselaer Polytechnic Institute
Amos Eaton Hall
Troy, New York

Robert Pinsoy
Department of Engineering
Case Institute of Technology
University Circle
Cleveland 6, Ohio

Dept. of Electrical Engineering
Case Institute of Technology
University Circle
Cleveland 6, Ohio
Attn: S. Seely, Head

Dr. C. J. Falkenback
Battelle Memorial Institute
Columbus, Ohio
Attn: Electrical Engineering Division

Librarian
Engineering Library
Brown University
Providence, Rhode Island

Professor A. W. Straiton
Dept. of Electrical Engineering
University of Texas
Austin 12, Texas

Mr. William Way
Research Librarian
Tasker Instruments Corp.
3349 Cahuenga Boulevard
Hollywood 28, California

SOLID STATE ONLY

Martin A. Garstens, Head
Paramagnetic Section
Magnetism Branch
Solid State Division
Naval Research Laboratory
Washington 25, D. C.
Attn: Code 6451

Dr. Reimar Brewken, Jr.
Ordnance Materials
Research Laboratory
Watertown Arsenal
Watertown, Massachusetts

Mr. A. Saiba
Himeji Technical College
Himeji, Japan

Electronics Research Laboratory
Division of Electrical Engineering
University of California
Berkeley 4, California
Attn: Librarian

Johns Hopkins University
34th and Charles Street
Whitehead Hall
Baltimore 18, Maryland
Attn: Mr. J. O. Artman

Librarian
Physics Department
Amherst College
Amherst, Massachusetts
Attn: Mr. Romer

Professor I. Lowe
Department of Physics
University of Minnesota
Minneapolis, Minnesota

Professor R. E. Norberg
Department of Physics
Washington University
St. Louis, Missouri

Microwave Research Institute
Polytechnic Institute of Brooklyn
55 Johnson Street
Brooklyn, New York
Attn: Librarian

Dr. Sidney Shapiro
Arthur D. Little, Inc.
15 Acorn Park
Cambridge 40, Massachusetts

Dr. Simon Foner
Lincoln Laboratories
Box 73
Lexington, Massachusetts

Mr. William H. Frown
Ewen Knight Corporation
256 A Street
Needham, Massachusetts

Dr. Edward U. Condon
6604 Waterman Avenue
St. Louis, Missouri

Dr W. M Walsh
Bell Telephone Labs., Inc.
Murray Hill, New Jersey

Librarian
IBM Watson Laboratories
612 West 115th Street
New York 27, New York

ELECTROMAGNETIC RADIATION ONLY

Michigan State College
Department of Mathematics
East Lansing, Michigan

Microwave Research Institute
Polytechnic Institute of Brooklyn
55 Johnson Street
Brooklyn, New York

Mr. L. E. Swarte, Jr.
Building 12, Room 2617
Hughes Research Laboratories
Culver City, California

Professor O. E. H. Rydbeck
P. O. Box 266
Delmar, New Jersey